FLATLANd: A Novel SDN-Based Telecoms Network Architecture Enabling NFV and Metro-Access Convergence

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***Abstract*— FLATLANd (Flat LAyer Two Large-scale Network) is a novel design for a Telecommunications architecture that is strictly flat and conducts traffic at layer 2 without the use of tunnelling, VPN nor labels. Because neither layer 3 nor layer 2.5 are used, higher layer networks can be overlaid cleanly onto this architecture. The architecture is inherently Open Access in that no one network nor service provider dominates over the others, as is the case in traditional wholesale and retail models for broadband access networks. Many of the layers and stacked components have been removed when compared to a traditional Telecommunications network. In this paper, we validate the proposed architecture for scalability, provisioning of basic and enhanced services and differentiation of services through bandwidth apportionment. We also present a basic power consumption model to show that FLATLANd has the potential to highly reduce energy utilisation in the core when compared to traditional Telecommunications networks.**

Keywords—Software Defined Network; SDN; NFV; Metro-Access Convergence; Open Access

I. INTRODUCTION

Traditional Telecommunications networks have evolved slowly over time, initially providing basic telephony services, then dial-up Internet access followed by higher speed ADSL. Unfortunately, the topology and components of the network (Fig 1) have remained unchanged, particularly in the access and metro portions of the network.

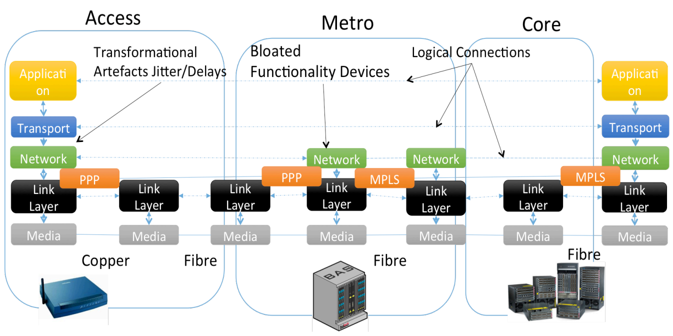

Fig. 1 Today's FTTH telecommunications architecture

Telecommunications networks have been slow to seize the benefits of newer fiber optics and Software Defined Networks technologies in the access. Traditional telecommunications networks are characterised by very long provisioning times and lack of flexibility in network bandwidth. There are multiple manual configuration actions to set up new services and customers, largely due to the lack of integration between the management systems of the technology stacks that support the service. Legacy network architectures are embedded in the control plane with the data plane in network devices, while Network designers typically use tunnels and VPNs to extend the reach of services. Fig. 2 shows a state-of-the-art approach where a Point-to-point-over-Ethernet (PPPoE) tunnel extends from a B-RAS (Broadband Remote Access Service) through to a Residential Gateway located in the customer's premises.

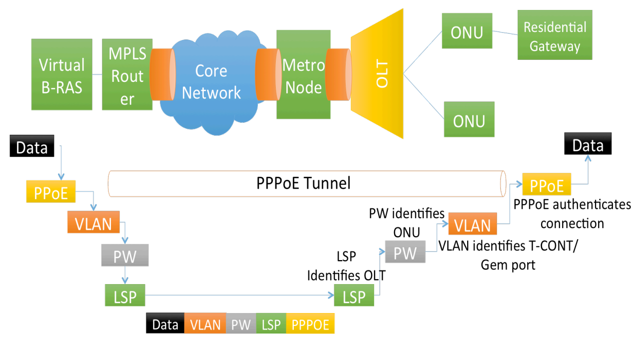

Fig. 2 State of the Art FTTH telecommunications

An MPLS router tags the PPPoE tunnel with a Pseudo-Wire (PW) identifier and a Label-Switched Path (LSP) label. The PW is used to identify the path up to the Optical Line terminal (OLT). For each OLT different PWs identify different SPs and within an SP different service types (Video-on-Demand and VOIP).After the OLT, towards the Optical Network Unit (ONU), a VLAN tag, together with the MAC address, is used by the ONU to direct traffic through a pre-determined Traffic-Container (T-CONT) and GPON Encapsulation Method (GEM) port. In the case of PPPoE, there are significant Virtual B-RAS load and capacity constraints. Tests done by BT [3] (for example showed a maximum limit of 9,000 PPPoE sessions per virtual B-RAS.

We argue that tunneling and encapsulation for the transit of large connection volumes has significant downside such as restrictive network partitioning, slow reconfiguration times, and suboptimal dissociation between network platform and services. Each network layer and hop that is traversed has the potential to introduce artefacts such as jitter, Bufferbloat and cross-layer authentication requirements. Bufferbloat [2] happens when excessively large (bloated) buffers are designed into network communication systems. Systems suffering from bufferbloat have bad latency under load under some or all circumstances, depending on if and where the bottleneck in the communication's path exists. Bufferbloat encourages network congestion; it destroys congestion avoidance in transport protocols such as HTTP, TCP and Bittorrent. Network congestion-avoidance algorithms depend on timely packet drop. Unfortunately, bloated buffers invalidate this design presumption.

Fundamental to our solution to these legacy issues is the use of NFV and SDN networks which have the advantages of being "*dynamic, manageable, cost-effective, and adaptable, making it ideal for the high-bandwidth, dynamic nature of today's applications*." [1]. We proceed by defining the basis of SDN and NFV, outlining our solution which we term FLATLANd.. We then validate our solution using some typical scenarios.

II. Software Defined Networks

The Open Network Foundation [4] defines Software Defined Network as a network "*architecture [that] decouples the network control and forwarding functions enabling the network control to become directly programmable and the underlying infrastructure to be abstracted for applications and network services*." The concept of Software Defined Network (SDN) appears in different categories of networks ranging from carrier networks, data centres and central office networks through to home and wireless networks. Also, SDN is relevant to physical, link, network and transport layers of the OSI and TCP/IP stacks, both individually but also in an amalgamation. While the Openflow protocols are synonymous with SDN for the configuration and management of flows at the data plane layer, it is one of a number of protocols that abstract the control plane from the data plane of network devices. The concept of the separation of control and data planes had been in existence for a number of years prior to Openflow catching the attention of first the research community, followed by switch manufacturers and software providers.

EU FP7 project SPARC (Split Architecture) [5] was an early project to demonstrate both SDN in the Access and Aggregation network as well as a prototype of Network Function Virtualisation, through a Virtual Home Gateway and a Virtual BRAS. There are two (so-called) splits in the SPARC architecture. Firstly, there is the split between the Control and Data planes that allows the data and control planes to evolve separately from each other. The data plane extends reach, connectivity and bandwidth, while the control plane enhances service creation, control and delivery. Secondly, there is the split between the forwarding and processing elements. In a traditional telco network, these functions are distributed throughout the network, for example at DSLAMs and customer home gateways with the result that these functions become isolated and degraded, though lack of manageability and enhancement. The split in forwarding and processing elements, is familiar in the concept Network Function Virtualisation, where simplified forwarding components at the level of data plane are located in the field or remotely, with the processing elements concentrated in either data centre or central office environments. SPARC respects the separation between access/aggregation and backbone/core networks, and leverages standard IP/MPLS control protocols such as OSPF, LDP, RSVP-TE and BGP to provide the necessary glue between control domains.

AT&T is implementing SDN in its core Telecommunications Network as part of its Domain 2.0 programme and predicts that there will be a reduction in cost per customer of $95 to $85 per annum. The AT&T Domain 2.0 programme impacts on AT&T's 4500 Cental Offices (CO's). Out of each Central Office, there are served 100'000 wired and 100'000 wireless subscribers. AT&T's has upgraded its core and access network and OSS architecture to Software Defined Network and Network Function Virtualisation through its Domain 2.0 Program. AT&T are one of the sponsor operators of the ONF's ONOS SDN framework [6]. Elbers et al [7] present a case study of Terastream. Deutsche Telecom Terastream network serves 40 Million fixed line customers, 115 Million mobile devices (via 70'000+ Cell sites) and 20'000 large enterprises. The large enterprise customers are connected to a three-tier architecture through an access layer composed of wireline, wireless and radio access. Tier 1 comprises 10-15 core router sites, the Tier 2 (metro) layer is composed of 1000 NG-POPS. There are 10k IP edge or aggregation nodes collocated with edge routers.

III. Network Function Virtualisation

ETSI promotes the standardisation for Fibre to the CAB (FTTcab), VDSL2 and G.Fast,. Most recently, ETSI has looked at which traditional components may be virtualised. [8] These components include GPON OLT's, ONU's, DSL DSLAM and Broadband Remote Access Servers (B-RAS) and home gateway devices. ETSI has a number of objectives in promoting NFV. These include optimisation of cost, reduction in the power consumption of remote devices, the relocation of complex functionality, that is currently located in the field, to the Head End, and the automation of provisioning of configuration and new services.. ETSI have defined a number of uses cases for NFV services. These use cases relate to the provision of virtual CPE (vCPE), Fixed Access Network Function Virtualisation, virtual Provider Edge (vPE) and virtual Basestation (vBS). The Virtual Network Functions (VNF) forwarding graphs use case describes how services may be chained together. Service chaining is also described by the Broadband Forum document SD-326. The Broadband Forum has a number of working groups looking at SDN as part of Broadband (SD-313), Access Networks (WT-358) and as an enabler for Flexible Service Chaining (SD-326) and Network Function Virtualisation (WT-359). [9] SD-313 is examining deployment scenarios where only some of the network equipments would support SDN functionalities, as well as possibility of supporting SDN capabilities by upgrading software only. EU FP7 project SPARC has successfully demonstrated the synergies between Software Defined Networking and Network Function Virtualisation through the separation (and subsequent concentration) of forwarding and processing elements found in traditional telecommunications networks.

IV. ARCHITECTURE AND FUNCTIONALITY

We propose the FLATLANd (Flat LAyer Two Large-scale Network) telecommunications network [11], which inherits the Portland [10] architecture for data centers (DC), as a paradigm to facilitate an efficient hierarchy of layer-2 switches and distributed Openflow tables (across ONU/OLT, electrical and optical switches). The Portland architecture uses Ethernet MAC addresses for routing traffic within the DC, where an address allocation policy assigns pseudo-MAC addresses to each host and organizes the addresses into a hierarchical topology [11]. In the FLATLANd architecture we apply the same concept to telecommunications networks. We claim that any network that uses Ethernet as a layer-2 protocol can benefit from the FLATLANd architecture. Rather than preserving legacy devices such as B-RAS in their physical or virtual form as does SPARC, we re-architect the entire network from first principles. We target in particular next generation optical broadband networks, and take into consideration the convergence of access and metro networks, suing the Long-Reach PON (LR-PON) architecture, discussed in [12], as a case study. Using protocols derived from XG-PON [13], LR-PON extends optical reach to customer ONU's to over 100Km, thereby bypassing the metro transmission network and enabling access-metro convergence through consolidation of central offices. The LR-PON has a larger split Ratio of 512, as opposed to 64 for XGPON. Layer-2 Ethernet addresses of network devices and terminations are assigned during manufacturing and thus uncorrelated to their location and other devices in their vicinity. This restricts their use in switched LAN and WAN segments, due to the impossibility to create any kind of hierarchical structure in the addressing scheme and forwarding tables. Through the use of pseudo-MAC addressing, the FLATLANd architecture (Fig. 3) overcomes such limitation by creating a structured Ethernet addressing domain that spans the entire network between the network terminations at the customer premise and the datacenter (Fig. 4), thus empowering wide area SDN at layer-2.

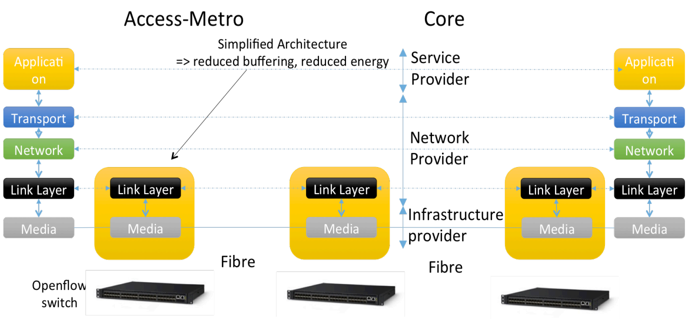

Fig. 3 FLATLANd FTTH architecture-level diagram

A translation is performed between the real (physical) address of the end device and the internal structured (pseudo) addressing used within the network. In the case of LR-PON, this translation is performed at the ONU GEM port. The mechanism partitions the internal 48-bit address space of an Ethernet layer into a number of arbitrary subfields, each routed to a different part of the network. The correlation between the real and pseudo addressing is performed dynamically by the SDN controller. For the LR-PON scenario we have identified a possible addressing scheme based on the following allocation: **'mm-tt-nn-cc-gg-dd'**. Following the structure in Fig. 5, **'mm'** identifies up to 4096 different metro-core nodes (12 bits), each with up to **'tt'** up to 4096 OLT ports (12 bits).

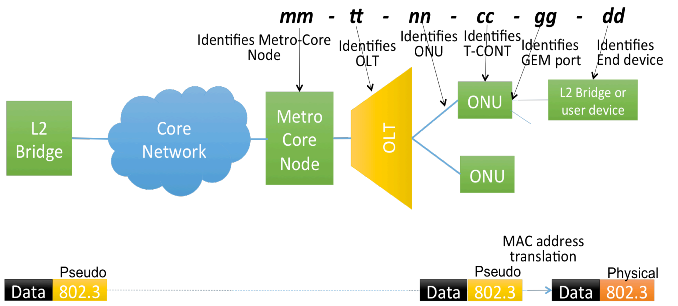

Fig. 4 FLATLANd FTTH function-level diagram

It should be noted that in the LR-PON architecture [12] a Metro-Core (MC) node is a converged node terminating both access and core connections, thus combining functionalities of access, metro and core nodes. Within an OLT port,'nn' identifies up to 4096 ONUs (12 bits), each with 16 **'cc'** T-CONTs (4 bits). A T-CONT is a group of logical connections that carries traffic within an ONU. Each T-CONT is identified by a unique Allocation Identifier (Alloc_ID) carrying traffic associated to one bandwidth type (i.e., QoS characteristic). The final 8 bits are split between GEM ports **'gg'** (4 bits or 16 GEM ports per T-CONT) and devices **'dd'** (4 bits or 16 devices per GEM ports). A GEM Port is a virtual port that encapsulates frames transmitted between the OLT and the ONU. Each traffic-class is assigned a different GEM Port. This would allow for example different users on the same ONU to acquire services from different providers concurrently. It should be noticed that we consider a classless address structure, where each block can have an arbitrary number of bits (up to a maximum sum of 48 bits, defined by the Ethernet address space limit). Also, we want to stress the fact that the proposed addressing scheme here provided is to be intended as an explanatory example, and different allocations can be assigned to suit the specific network architecture considered.

The benefits of the flat layer-2 approach are exemplified by contrasting today's (Fig. 1) and the proposed (Fig. 3) architectures. Firstly, we see a flattening of layers within the access and metro portions of the network. This is caused by some functions, such as B-RAS and PPPoE terminating modems being made redundant, and other network functions such as AAA services (Authentication, Authorization and Accounting) being virtualized at the periphery of the network, following an NFV approach. Secondly, there is potential for significant Capex and Opex improvements (reduced Operations and Maintenance) due to the adoption of white-boxes Openflow-based switches controlled by a unified SDN control plane. Thirdly, the network is inherently Open Access [14] in that the roles of infrastructure provider, network provider and service provider can be clearly demarcated. All devices are granted access to the network but subsequently may be dynamically or statically bound to the profile of a target service provider. Indeed the flexibility of the addressing scheme favors multi-tenancy, as parts of the address can be used for packet routing purposes and other parts for QoS and SP differentiation. Distinct flow rules are created for the metering of each class of traffic at each Metro-Core node, OLT and ONUs. These are separate from the rules necessary for forwarding flows.

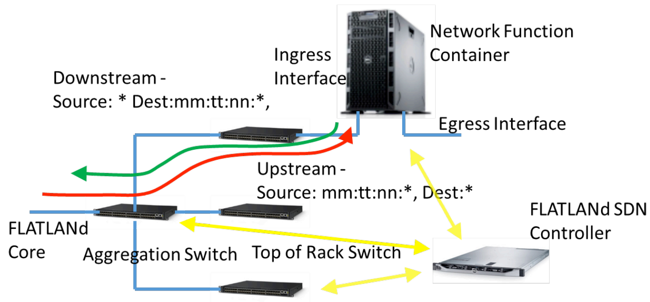

Fig. 5 FLATLANd Network Function Container

In the FLATLANd architecture, Network Functions are classified as either either service-control or in-line. Examples of service-control are service authorisation and service binding. Examples of in-line services are services that impact or touch the actual traffic being generated by an end-user, examples of which are firewalling and traffic monitoring and control and the ETSI vCPE. Figure 5 shows how the in-line services are provided in the datacenter, with dedicated processing allocated to each network terminating device such as an ONU. A multi-tiered Openflow based switch network connects Aggregation and Top of the Rack (ToR) layers. The centralised FLATLANd SDN Control function that directs the Core, Metro and Access network, also directs the datacenter NFV functions. Where there are 4 million ONU's then an equal number of Virtual Machine's (VM) would be allocated within the datacentre. The working ratio of VM's to physical machines is 20:1, however this ratio maybe altered upwards or downwards on an individual basis. FLATLANd provides the equivalent of a virtual network between the customer terminating network and the VM in the datacenter. Each VM has two virtual interfaces, one of which faces into the FLATLANd core, the other faces into the public or provider network. In its simplest form, these virtual interfaces maybe bridged in order to connect the terminating network with the public or provider network, or may form the ingress and egress interface of a single in-line network function such as a firewall or a chain of network functions. The virtual interfaces are opened in raw socket mode, so the ethernet encapsulation (pseudo-mac) addresses and thereby preserving the identity (source MAC address) of the remote devices. Flows within the datacenter rely on the hierarchy of addressing. Upstream traffic flows that match the wild-carded **source** pseudo-mac address **mm:tt::nn:*** are directed through the switched network according to openflow rules injected into the aggregation and TOR layer switches by the SDN controller. Similarly, downstream traffic match wild-carded **destination** pseudo-mac address **mm:tt::nn:***

Traditional Service Providers have built dedicated networks so as to differentiate their services from other offerings. Differentiation has been based on factors such as availability and bandwidth. In the FLATLANd design, since a common infrastructure is shared across all Service Providers, FLATLANd employs mechanisms for bandwidth apportionment that are distributed throughout the network. Fig 6 shows the contiguous 48-bit address range. 36 bits of the address relate to the routing of traffic across the core and metro networks to an ONU. This is composed of Metro Core, OLT and ONU address portions. 12 bits of the address relate to the identification of Service Provider and Service Type. Bandwidth apportionment may be performed at the root of the network, which has visibility of all traffic flows in the network, however, that would require a contiguous flow table which is unfeasibly large (with potentially 2^48 i.e. 2 to the power of 48 entries).

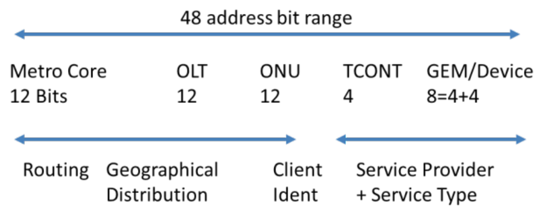

Fig. 6 48-bit Address Range

The FLATLANd architecture allows two main approaches for distributed bandwidth apportionment: Geographical and per-Class. Geographical bandwidth apportionment applies control to the flows traversing each network element. For example, in order to apportion bandwidth according to a per-OLT basis, rules need to be applied at the upstream Metro Core network. In order to apportion bandwidth on a Service Type or Service Provider basis in the Geographical model, rules need to be applied to the upstream TCONT and GEM ports. The existing flow rules can be modified with the meter tags on the output action. Per-Class applies control to the flows traversing each network element. The key difference with the Geographical model, is that distinct flow rules are created for the metering of each class of traffic at each Metro-Core, OLT and ONUs. These are separate from the rules necessary for forwarding flows. The advantage of per-Class bandwidth apportionment is that there is greater control over each Class of service across the network, whereas with Geographical, there is probably more efficient use of bandwidth.

V. Functional Validation

We validated the operations of the SDN controller in the FLATLANd architecture in the stages required to register an ONU device with a given Service Provider: first pseudo address allocation and then layer-3 authorization. We validated the FLATLANd address partitioning and mapping scheme by replicating the 6-tier network hierarchy shown in Fig. 5, and test key NFV functionality such as service registration. Service registration is the process that allows each network element to obtain a pseudo-MAC address unequivocally associated to its physical MAC address, thus enabling its association to the FLATLANd network, and Layer-3 authentication. To validate the functionality on a virtual environment implemented on the Mininet platform [15]. A custom Openflow controller was developed, derived from the base POX implementation, and extended with memory-based Redis database. The Redis database is low-latency and can be (geograpically) distributed across many physical machines, with some implementations handling millions of queries per second. Redis preserves transactionality between nodes. While there is a single master read/write node, changes in this database can be instantaneously mirrored across many read only nodes. For the current purposes, the database maintains the mappings between all real-mac, pseudo-mac addresses, IP addresses, and flows both in the network in the datacenter for the virtualization of Network Functions.

Fig. 7 shows the emulated network architecture, inclusive of emulated latency times between the network elements (the values used are only indicative of the LR-PON case study considered), and the client binding and registration process. The test initiates with the Layer-2 Bind Phase, where the client device at the GEM port of the ONU registers its interface on the network. This interface is configured to obtain its IP address from a DHCP server, situated centrally and upstream from the device.

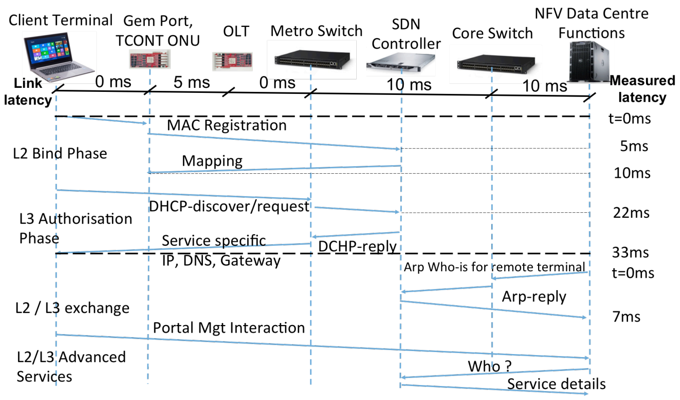

Fig. 7 – Service Registration carried out on SDN/NFV testbed

On sensing of a DHCP-discover/request packet, the layer-2 of the customer Openflow-enabled ONU, sends the DHCP packet to the centralized Openflow Controller [16]. At the ONU the OpenFlow switching is operated by the ONU GEM port switch. The Openflow Controller then performs three actions. Since the Openflow Controller knows the ONU from which packets are received, the controller formulates a pseudo-MAC address appropriate to that ONU. The Openflow Controller database creates a forward and reverse mapping between the real- and pseudo-MAC addresses to allow fast database lookups. The mapping is then sent to the ONU as an Openflow rule. The layer-3 authorization phase is required for the ONU client to receive appropriate network layer facilities such as IP address, DNS settings and Gateway addressing. The system operates by the Openflow controller intercepting a DHCP-discover/request either as part of the layer-2 bind phase or as a retransmission of this request. The Openflow Controller constructs a DHCP-reply packet with the appropriate settings, for transmission through the ONU switch, to the client. The Openflow Controller also constructs per-Service Provider IP addresses and DNS settings. In the ARP Exchange Phase, the end-points exchange IP addresses and MAC address pairings. Where the client device sends an IP packet to a data center, the ARP who-is request is broadcast upstream and the upstream device responds with an ARP response. The GEM Port switch performs a swap of real- and pseudo-MAC addresses for the client device. The metro switch intercepts the ARP who-is request destined for the pseudo-MAC of the client device. Finally, the controller performs a proxy-ARP functionality based on the pseudo-MAC address of the client device.

To demonstrate the NFV functionality, a single layer datacenter switch was instantiated with small number of rules to direct the upstream and downstream traffic flows to and from the Network Function Virtual Machine. Linux LXC Container technology was used for the virtualisation, with the advantages that a low storage and processing overhead is imposed on the host environment. A basic traffic application was deployed on the Network Function Container, which both transited traffic between the ingress and egress interfaces as well as inspected and logged packet headers and payload.

The testbed results show that registration times of around 30 ms can be achieved for the LR-PON based scenario shown in Fig. 6. While such operations are generally not time-critical, these results demonstrate the type of benefits that a simplified SDN-driven flat architecture can bring about. Once registration was complete, we successfully transmitted traffic between the client and datacenter end-points. The traffic included both typical HTTP web traffic, but also less conventional Ethernet frames more suited to the transit of IoT device traffic.

VI. PERFORMANCE

We modelled the Power consumption of the FLATLANd network, given typical parameters for a 3-tier switch network. We assumed that the traffic contention ratios on the Core-Metro, Metro-OLT and OLT-ONU links were 2, 5 and 20 respectively with a small size network of 4 million termination points (ONU's). With a theoretical maximum number of ONUs of 68.2 billion possible on the FLATLANd architecture, the ONU fill-factor 0.6.This fill factor can be built through selection of 4 of all ONU's, on 4 of all OLT's in turn on 4 of all Metro nodes. The Bundle Factor is an aggregation of the contention, Maximum distribution of flows and Occupancy, and represents the level of real connections between elements such as an ONU and an OLT. With an average device bit rate of 1 Mbps, we can calculate the traffic handled by each element at the 4 stages in the network. For the switches in the network, we assume the parameters of a Pica8 Pronto P-3922 Openflow switch. This has 48 10Gb ports, and expends a steady state consumption power of 250W or 5.2W per port. With a total of 4.025 million ports in the network, the total switch power consumption 0.264 MW for the core elements. For this calculation we define the core network as all components other than the ONU switches.

We calculate the core network power consumption as 0.0661 Watts per subscriber W/sub. This is substantially less than the power consumption calculated by Vereecken [17] of 0.24W/sub for the core of a traditional telecommunications network where ADSL is used as the access method. We predict also that core network power consumption decreases to 0.011W/sub as the number of subscribers increases from 4 million to 1 billion. There are differences in the comparison in that FLATLANd currently does not assume protection in the core. When the power consumption of the ONU switches are included, then total power consumption per consumer increases to 5.274W/sub. This is larger than the 3W/sub predicted by Vereecken et al, for a traditional telecommunications network with access speeds of 100Mbps. The excess can be explained due to over-specification of the ONU switch port in our model. The total power consumption for a network of 4 million subscribers, comprising all switches, is 21.098 MW.

We recognise the impact and challenges in concentrating the ARP functions for an entire network in a small number of locations. In classic architectures, the function of ARP address resolution is distributed to each Layer 2 broadcast domain, in particular at the terminating LAN and wifi networks. In total, the number of hosts generating ARP queries and seeking ARP responses for an entire network could run into the hundreds of thousands or millions per second. However, centralisation of ARP is an important network control network, already implemented in large datacenters and can be quantified. In the Portland model [10], it is assumed that each ARP requires 25 microseconds execution time with an ARP timeout of 60 seconds and each ARP packet is 28 bytes long. Using the model proposed, for a Flatland network with 4 million terminating ONU's, each generating 1 Arp request per second, would require a 100 Core processors, which may be parallelized and distributed to 4 or 5 geographical areas in the network. In total, Arp queries and responses generates 896 Mbps of traffic.

VII. CONCLUSIONS

In this paper, we presented a flat layer 2 architecture for telecommunications networks that allows removing many components traditionally active in telecommunications architectures, while still retain much of the functionality for access and the delivery of service. Since a number of layers (such as PPPOE tunnelling) and component stacks (such as Broadband Access Services) are removed, there is less requirement for authentication and authorisation across junctions between these layers. This allows for much potential in Opex and Capex savings through reduced equipment plant in the metro and access networks. With less layers (such as PPPoE tunneling) and component stacks (such as Broadband Access Services), the requirement for cross-layer authentication and authorization is greatly reduced. In addition, the FLATLANd architecture provides a separation between the provision of infrastructure, network services and Internet services by distinct entities, potentially enhancing efficiency of use of resources. While the topology we focused on, in the metro-access, was a tree structure, the principles should apply for other topologies such as ring and hub which form the basis of Ethernet networks.

VIII. ACKNOWLEDGMENT

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